U.S. DEPARTMENT OF COMMERCE
National Technical Information Service

AD-A033 815

IMPROVING JET ENGINE RELIABILITY AND MAINTAINABILITY: A CONCEPTUAL APPROACH

DEFENSE SYSTEMS MANAGEMENT SCHOOL
FORT BELVOIR, VIRGINIA

5 MAY 1976

DEFENSE SYSTEMS MANAGEMENT SCHOOL

PROGRAM MANAGEMENT COURSE
INDIVIDUAL STUDY PROGRAM

IMPROVING JET ENGINE
RELIABILITY AND MAINTAINABILITY:
A CONCEPTUAL APPROACH

STUDY PROJECT REPORT
PMC 76-1

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) IMPROVING JET ENGINE RELIABILITY AND MAINTAINABILITY: A CONCEPTUAL APPROACH		5. TYPE OF REPORT & PERIOD COVERED Study Project Report 76-1 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) John D. Masson		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS DEFENSE SYSTEMS MANAGEMENT COLLEGE FT. BELVOIR, VA 22060		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS DEFENSE SYSTEMS MANAGEMENT COLLEGE FT. BELVOIR, VA 22060		12. REPORT DATE 76-1 13. NUMBER OF PAGES 43
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) UNLIMITED DISTRIBUTION STATEMENT A Approved for public release Distribution Unlimited		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) SEE ATTACHED SHEET		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) SEE ATTACHED SHEET		

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

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DEFENSE SYSTEMS MANAGEMENT SCHOOL

STUDY TITLE: JET ENGINE RELIABILITY AND MAINTAINABILITY: A SUGGESTED APPROACH

STUDY PROJECT GOALS: To identify the factors in the engine life cycle that have a significant affect on reliability and maintainability. To develop and suggest a conceptual approach for obtaining improved reliability and maintainability in jet engines.

STUDY REPORT ABSTRACT: The purpose of the report is to identify those factors occurring during the life cycle of an engine that significantly affect reliability and maintainability.

The purpose of this report is to propose a management approach to be used to improve jet engine reliability and maintainability. The need for improvement is established through an examination of the life cycle of an engine, the estimated costs, costs associated with each life cycle phase, and the factors occurring during each phase that significantly affect reliability and maintainability. This review concludes that significant changes to the engine development and acquisition changes are not practical. The proposed approach is intended for use within the existing engine life cycle framework.

KEY WORDS: Jet Engine Reliability-Maintainability.

MATERIEL DESIGN AND DEVELOPMENT ENGINES MAINTAINABILITY AIRCRAFT ENGINES LIFE CYCLE COST

RELIABILITY
PROGRAM MANAGEMENT

NAME, RANK, SERVICE	CLASS	DATE
JOHN D. MASSON Major, USAF	PMC 76-1	6 MAY 1976

IMPROVING JET ENGINE
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DEFENSE SYSTEMS MANAGEMENT SCHOOL
PROGRAM MANAGEMENT COURSE
CLASS 76-1

by
JOHN D. MASSON
Major, USAF

5 May 1976

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This study project report represents the views, conclusions, and recommendations of the author and does not necessarily reflect the official opinion of the Defense Systems Management School of the Department of Defense.

EXECUTIVE SUMMARY

The objective of this paper is to offer the engine program manager a management tool that will enhance his ability to improve jet engine reliability and maintainability.

It was found that there are many significant factors in the early phases of the engine life cycle that tend to shift concern for reliability and maintainability to the production phase. These factors are reviewed first, through an overview of the engine life cycle and the costs associated with each phase of the life cycle and, secondly, through a detailed examination of the problems faced during the design, development and production processes. The conclusion reached as a result of this review is that major changes to the engine acquisition process are not to be expected and therefore, improvements in reliability and maintainability can only be gained through improved management procedures within the existing process.

The author's conclusion was that an improved management approach was dependent on the development of two factors. First, a standard of measure that can be used to establish realistic goals and provide timely feedback is required. The second required factor was a method to motivate both contractor and government personnel towards obtaining improvements in reliability and maintainability.

The paper suggests that an appropriate standard of measure would be the ratio of "equivalent maintenance actions" to "engine flight hours". Examples are presented of how this ratio would be established and used during and after the development cycle. The suggested motivational

technique contemplates tying a modified award fee concept to goals based on the aforementioned standard of measure. An explanation is given of how these concepts could be applied to achieve improved reliability and maintainability.

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SECTION I

INTRODUCTION

The purpose of this paper is to suggest an approach that may provide the engine program manager and the development contractor with a management tool designed to achieve increased reliability and maintainability in aircraft jet engines. The need for improved engine reliability and maintainability is indicated by the following extracts from a Memorandum for General William J. Evans, Commander, Air Force Systems Command from Assistant Secretary LaBerge dated 17 September 1975, Subject: Contractor Warranties and Liabilities.

> "The continuing problems associated with the durability and reliability of our jet engine assets clearly should motivate the Air Force to carefully examine all prospects for achieving a greater responsibility for their products. I continue to believe that some form of shared responsibility between the government and the engine contractor can be achieved which, although not a true warranty, could significantly reduce the kinds of engine problems we are experiencing today.
>
> "My repeated attempts to draw out the contractors on this subject have been consistently countered with the very strong arguments that the military application of engines effectively precludes any such considerations. The very restrictive specifications associated with engine development and procurement, lack of definitions regarding operating requirements, military autonomy of ECP and configuration control and military logistic support, are just a few of the elements that combine to present a risk too large to be accepted by even the most aggressive engine developer.
>
> "Given this situation, I have become convinced that the only possibility for achieving any perceptible progress toward greater contractor responsibility lies in exploring the way in which the Air Force could undertake to lower or remove these hurdles.
>
> "The purpose of this memorandum is to solicit your thoughts on how the Air Force might best attack this problem....it. The impasse which currently exists demands a fresh approach and surely the initiative rests with the Air Foce if any progress is to be made."

This paper will provide an overview of the engine life cycle and identify the problems experienced in the engine acquisition process. The suggested approach and supporting rationale shall conclude the report.

SECTION II

THE ENGINE LIFE CYCLE

The realistic life span of an engine model, from the start of basic research through disposal, can run forty or more years. This life span can be divided into three distinct phases as depicted in figure one. The first phase lasts approximately thirteen years. During this period, approximately ten years are spent in basic research of new materials and concepts with the balance of the period devoted to advanced development and feasibility studies to demonstrate the validity of the basic effort. The second phase, lasting approximately eight years, is used to develop a specific engine for a specific application and, in turn can be further subdivided into two segments. The first segment, lasting about five years, is the development effort preceeding the military qualification test (MQT)[1] and the start of production. The second segment, lasting two to three years after the start of production, is the development effort devoted to maturing the engine design based on the results of continued flight testing and operational use. Finally, during the third and final phase, the engine will have a useful life of from five to twenty years in the operational inventory. (3:20-21) [2] (See Figure 1)

1 Military Qualification Test - The test required to demonstrate required performance/endurance characteristics. Successful passage of this test ends the official development period and permits the start of delivery of production engines (Also called Model Qualification Test).

2 This notation will be used throughout the report for sources of quotations and major references. The first number is the source listed in the Bibliography. The second number is the page in the reference.

A reader familiar with the "real" world of military aircraft turbine engine development may not recognize the preceeding description of the life cycle of an engine model. He has good reason for not recognizing it. First the life cycle described above was for the development of a totally new engine. The majority of "new" engines acquired by the military during the last twenty years have been modifications of proven basic engine configurations. Normally the development of a new/modified engine can be expected to take less time than a total development effort. The second, and perhaps more valid reason for the reader not recognizing this description of an engine life cycle is that historically, in order to meet a weapon system initial operational capability (IOC) date, there has been a compression of the development after MQT.

The problems resulting from a compressed development period can be compounded by the fact that production lead time for engines range from fifteen to twenty-three months and delivery of the first production engine is normally required to be made shortly after MQT. Thus if a three to four year development period is planned, long lead production effort begins while there is approximately one-half to one-third of the development effort yet to be accomplished. The concurrent development of both the engine and the airframe may result in the further compression of the engine development program vis-a-vis the airframe development program by the necessity to deliver engines to the airframe manufacturer three to six months prior to the aircraft delivery date. (See Figure 2)

FIGURE I

IDEALIZED ENGINE LIFE CYCLE

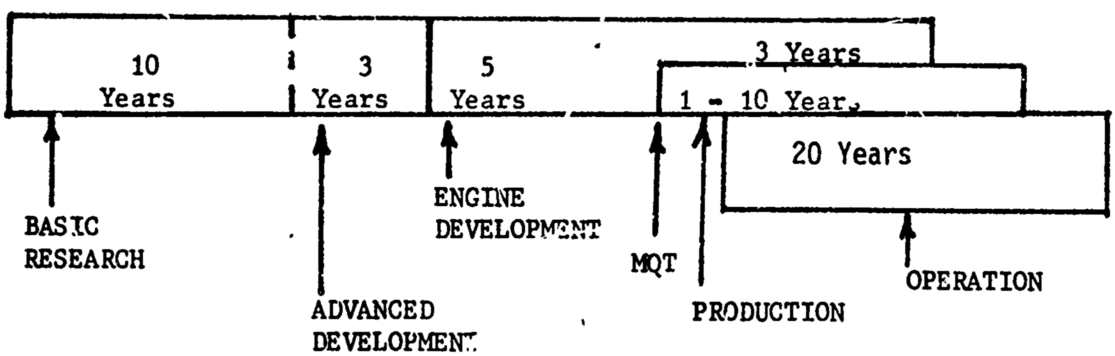
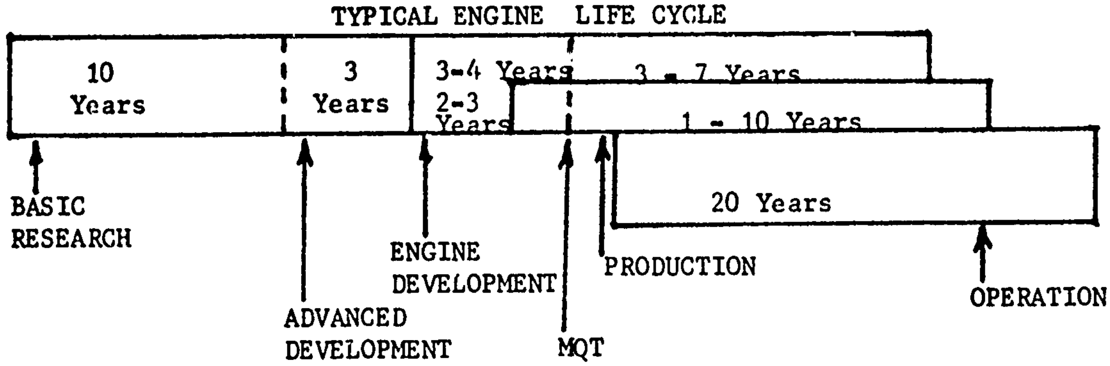


FIGURE 2

TYPICAL ENGINE LIFE CYCLE



These compressed time frames, as well as other considerations, have lead to the formalization of post-MQT development programs that, in the Air Force, are known as Component Improvement Programs (CIP). These programs are contracted for on an annual basis with the development contractor. Prior to 1969, Component Improvement Programs were used to enhance performance and explore additional applications for the engine as well as to correct deficiencies and improve the "ilities" (i.e., reliability, durability, maintainability, etc.) However, since 1969 CIP effort has been directed solely towards correction of deficiencies and improvement of the "ilities". Several studies have indicated that as much or more money is spent on post-MQT development (CIP) as is spent during the pre-MQT development period. One such study of eight engines revealed that, in terms of 1975 dollars, the cost to achieve MQT was $1.9 billion while the cost of CIP effort subsequent to MQT was $3.1 billion. (9:39)

The question that must be answered is whether or not the approach being used to acquire engines has had any adverse effect on reliability, maintainability, and life cycle costs. Several studies have been made to determine the spread of costs over the life cycle of an engine. The earlier studies indicated that only one-third to one-fifth of the life cycle cost was consumed by the costs of ownership. These findings imply that there is little room for reducing life cycle costs by increasing the cost of development. (9:11-17) However, a subsequent study of engine life cycle costs found that these earlier studies suffered from sufficient poor assumptions, problems of definition, and data interpretation to make the study results suspect. While this study concluded that an accurate determination of the life cycle cost of an engine cannot be made because of the inadequacy of the data available it strongly indicated that the cost of ownership exceeds the cost of acquisition. (9:60)

Assuming that the indications of this later study are valid, it would seem that there may be sufficient leverage available to gain significant life cycle cost benefits from an additional investment in development. One study to evaluate this possibility was based on the F100-PW-100 engine, used in the F-15, and assumed that 2000-3000 engines with an average fifteen year life would be acquired. Through the use of a development cost model it was determined that for $100,000,000 an additional one to one-and-a-half years of intensive ground and flight testing could be acquired. If this effort resulted in the elimination of one overhaul per engine it was determined, through the use of an overhaul cost model, that a savings of one-half to one billion dollars would accrue to the government. (9:62)

Neither the validity of the models used, the cost factors, nor the assumptions used in the aforementioned study were examined for the purpose of this paper. However, another study has resulted in similar conclusions. This study used models to optimize the reliability of four weapon systems and applied cost models to determine the additional development costs that would have been required to achieve the optimized reliability and its affect on life cycle costs. The indications were that had an additional 7.8% of life cycle costs been invested during development a net savings of 27% of life cycle costs could have been achieved. The models also indicated that there would have been a collateral benefit of increasing the probability of mission success for each of the four weapon systems by 54%. (4:71)

In Section II we have addressed the engine life cycle, the costs related thereto, and examined some studies that imply that substantial life cycle cost savings can be achieved through increasing our investment during the development period. In Section III we shall examine some of the problems experienced during development that have precluded full realization of the potential benefits.

SECTION III

DEVELOPMENT FACTORS

One of the difficulties with studies such as those addressed in Section II is that they are "what if we had" exercises. There is no practical way to confirm them or determine that an investment of a given magnitude in development will result in a measurable benefit during the useful life of an engine. Although we can not confirm the validity of the models through empirical testing, they can be used as an indicator of the potential for savings in life cycle costs for a relatively small investment during the development period. We can also look to other areas, such as the electronics field, where significant reductions in life cycle costs have been obtained, through increases in reliability and maintainability.

If this potential for reducing life cycle costs is available why hasn't this potential been exploited to its fullest? There are many interrelated and non-related factors encountered during the development process that have precluded realization of these benefits. In this part we shall look at each phase of the development process to review what these factors are and what impact they have on life cycle costs. The phases are respectively ....

PRE-DEVELOPMENT PHASE

As noted in Section II the effort in this phase consists of basic research and concept demonstration. It will be shown that, because many factors have not been defined at this point in time, little, if any, improvement in the "ilities" can be obtained during this phase.

"The achieved levels of reliability and durability depend on three interacting factors; inherent reliability and durability, the operational plan, and the support plan". (11:3) Inherent reliability and durability are determined by the design of the components of the engine. At this point, however, there has been no effort to establish any specific design objectives or criteria, thus the data obtained from the tests conducted in this phase is of limited value in terms of reliability and durability. One reason is that much of the testing is done on scale models which may or may not duplicate the environment the part will see in a full-sized test model. Secondly, between the point of concept testing and the point in time at which a full-sized test engine developed for a specific requirement is available for testing, the design of the part or parts will, in all probability, have changed many times. A third reason that reduces the usefulness of data from this phase is that there is relatively little concern over the weight of hardware being tested. Thus the hardware can be made extremely durable by increasing its weight. However, engine system specifications generally establish thrust and weight criteria that must be met. If, in order to meet these criteria, the weight of the test hardware has to be changed on a disproportionate basis, the test data has little value. Thus, although the concept demonstrations are of value in determining the validity of a concept, they are of little value in establishing data that can later be used to predict an inherent level of reliability or durability.

The second missing factor affecting the achieved characteristics of an engine is the mission operation plan or mission profile. The affect of the mission profile on the achieved capability of an engine was indicated in one study of the J79-GE-15 engine used in both the F-4 and RF-4 weapon systems. In these weapon systems the engines are identical and the airframes are basically the same. The differences occur between the mission profiles flown and the hardware carried. The study found that there was a thirty percent difference in the time-between-overhauls (TBO's) between the engines used in the F-4 and RF-4 systems. (3:16)

The third factor affecting the achieved capability of an engine, the mission support plan, is also absent in this phase. This plan determines the allocation of the quantity and quality of the resources that are to be devoted to the maintenance of an engine. It also establishes guidance on the repair policies that will be used. As these policies will govern the number of parts to be replaced when a related part has failed they can affect the achieved capabilities in either a positive or negative manner. The importance of the support plan and the way in which it is implemented can be inferred from one study which indicated a difference in time-between overhauls between units of the same weapon systems flying the same mission but from different bases. (11:4)

To summarize, the pre-development phase has proven to be of little value in improving the "ilities" because of the absence of three critical factors: design objectives; mission profile; and, mission support plan.

DEVELOPMENT PHASE

At the start of the development phase the design objectives, mission profile, and mission support plan will have been defined in some detail. Thus, the development phase is the key to minimizing life cycle costs. The design concepts established during the early part of this phase will determine where, how, and how much a substantial portion of the life cycle costs will be incurred. In discussing this phase we will look first at some of the problems the designer has in predicting the "ilities", then at the contractor's design process and, finally, at the manner in which we specify requirements and the trade-offs facing the program manager.

PREDICTING INHERENT RELIABILITY

Designing an engine is partially a scientific effort and partially a mystical art. One indication of the difficulty encountered in designing an engine can, perhaps, be shown by comparing the problems faced by the engine reliability engineer and those faced by an electronics reliability engineer in formulating reliability test plans.

The first assumption that can be made by the electronics engineer is that the failure distribution of items being tested is exponential (i.e., a constant hazard rate). With engines, a constant hazard rate is not achieved until between 100,000 and 200,000 engine operating hours have been obtained. It normally takes about three years of field usage to accumulate this number of operating hours.

The second assumption available to the electronics engineer is that samples can be taken from a homogeneous population in which all of the items contain the same parts. Historically, the engine acquisition cycle has been characterized by a relatively high rate of engineering changes in the first two to three years after the start of production. These changes are incorporated in the engine on a relatively random basis depending on the urgency of need and the expected cost. For example, changes to correct a safety of flight problem are incorporated immediately, both in the field and in production, while less urgent changes will be incorporated in production at the most economical point with the retrofit of previously delivered engines accomplished on an attrition basis or at the time of next overhaul.

The third assumption used by electronic engineers is that all items will be tested simultaneously under the expected environmental conditions. Both the internal and external environment in which an engine operates is far broader than that normally experienced by electronics or avionics equipment. Further, the interface characteristics of the airframe with the engine has a major impact on the internal environment of the engine. Thus in order to adequately test an engine it would have to be done in a simulated altitude environment. The facilities for such tests are extremely limited and expensive to operate thus precluding significant amounts of testing on a parallel basis.

The final assumption, that we will review, available to the electronics engineer is that the failure of one component will not hasten or delay the failure of another component. With engines a fa   e of one part can not only hasten the failure of another component, it may physically destroy the other component or components. (11:1-3)

THE DESIGN PROCESS

To arrive at a preliminary engine design layout the contractor's design engineers go through four general steps, which may be repeated many times, to arrive at the final product. These steps are:

1. Mission study - a simulation of representations of both the aircraft and engine to determine engine thrust, flight altitude, Mach number, and flight time for each segment of the specified mission.

2. Engine performance analysis - a computer simulation of the engine operation over the entire flight regime to obtain a detailed definition of the air flow, fuel flow, rotor speeds, and pressures and temperatures that will be required.

3. Aerodynamic design - the design required to define the gas flow path of the engine.

4. Mechanical design - the design of the required hardware components. (8:16-18)

During this iterative design process there is, of course, concurrent design effort on reliability, maintainability, durability, etc. A brief review of the process followed to design for durability and reliability will serve to demonstrate the problems faced by the design engineer in developing an engine with acceptable characteristics.

One of the more widely used approaches in designing for durability is called life consumed analysis. The objective of this analysis is to ensure that parts will have a uselife of a specified number of hours. The data obtained from the mission and engine performance analyses are used to construct tables that identify temperatures, loads and time at temperatures and loads for various points in the engine. Materials and designs that will survive under these conditions for the specified time are then selected, developed and tested. If the tests are not successful, the process is repeated until success is achieved. There are some weaknesses to this type of analysis. First there are differing opinions as to whether or not a "useful life" permits periodic repair of the item. Depending upon which definition one agrees to will make a significant impact on life cycle costs. Secondly, the analysis does not consider the effects of the sequence in which stresses are applied to parts nor does it consider the effect of other phenomena such as cyclical fatigue. It has been demonstrated that these latter factors do have a marked effect on the life of a part. Despite these weaknesses, life consumed analysis is beneficial in that it results in a disciplined approach for designing for durability. (8:18-20)

Determining the reliability of an item generally follows a process of logic which includes defining each part and its hierarchal relationship to the end item; identifying the failure processes that each part is susceptible to; defining the failure rate for each process, determining the probability of failure and the sequential affect of a failure up through the hierarchy of subsystems, components and end items; and, determining the overall reliability of the end item. It would be convenient if the design of parts could follow this chain of logic. However, relatively few parts are designed on an analytical basis because of the expense involved. Most of the parts in an engine are designed on the basis of experience and intuition, built, tested, and rebuilt until an acceptable reliability level has been achieved. The reliability factors for all parts are then combined to determine the reliability of the end item. If end-item reliability is not acceptable then the design is iterated until an acceptable level is achieved. The effectiveness of this "build, test, rebuild" approach is dependent on the availability of sufficient time and money to conduct testing. The General Electric Company has, in fact, developed a model which uses reliability growth as a function of development test hours to determine the number of engines, test cells, and development test hours that are required to achieve a given level of reliability. (8:20-24)

The design approaches used to insure acceptable levels in the other "ilities" are equally complex, based on the "build it, test it, rebuild it" approach, and equally dependent on the amount of testing that is to be accomplished. Before the contractor can start his design, however, he should know what levels are acceptable. This information can be found in the Request for Proposal and the contract - at least in some form.

CONTRACT REQUIREMENTS

The Logistics Management Institute has reviewed the requirements for reliability, maintainability, and durability set forth in the Requests for Proposal and contracts for several engines. (8:13) Their findings are summarized below:

Engine: F101 Weapon System: B-1

RFP requirements - None. In lieu of a specific requirement the RFT contained the following: "The contractor is to conduct reliability and maintainability programs in accordance with, respectively, MIL-STD-785 and MIL-STD-470. From these programs the contractor is to establish reliability requirements to be specified in the engine specification. Maintainability projections for the mature engine (one and one-half years after IOC) are to be made."

Engine: T63 - A5 Weapon System: OH-6A

Contract Requirements: Reliability - Mission reliability = .985 for 3-hour mission; unscheduled Maintenance Reliability = .868 for 3-hour mission. Maintainability - Organizational and Direct Support Maintenance man hours = .177 man hours/flight/hour. Durability - None.

Engine: J79-17 Weapon System: F4

Contract Requirements: Reliability = .995 for 1 hour. Maintainability - Periodic inspection to consume less than 150 maintenance man hours (goal of 35). Several accessories have remove and replace man hours per 1000 operating hours. Goal of 1 maintenance man hour per flight hour. Durability - Goal of 1200 hours time between overhaul and 600 hours between inspection.

Engine: TF-30 Weapon System: F-111

Contract Requirements: Reliability - The objectives are 500 hours mean time between failure (MTBF) at 5000 flight hours and 1000 hours (MTBF) after 100,000 flight hours. Maintainability - None. Durability - None.

Engine: F-100 Weapon System: F-15

RFP requirements: Reliability - None. Contractor is to conduct a reliability program (MIL-STD-785) and determine the mean-time-between-in-flight-power-loss (MTBIFPL) and mean time between unscheduled maintenance (MTBUM) to be demonstrated in category II testing and also project the MTIFPL and MTBUM to be achieved by 200,000 engine hours. Maintainability - None. Contractor is to conduct a maintainability program (MIL-STD-470) and determine corrective and preventive maintenance man-hours per flight hour. Durability - Cold section life = 6000 hours. Hot section life = 3000 hours. All parts to have low cycle fatigue life of 12,000 hours.

Contract Requirements: Reliability - Predicted MTBF of 1000 hours one and one-half years after IOC. Predicted MTBF of 270 hours at end of category II testing. Maintainability - Predicted organizational and base maintenance man hours of 2 per flight hour. Durability - same as RFP.

The requirements set forth in the above Requests for Proposals and contracts are not very firm nor are they very binding. Does this mean that our requirements are poorly written or does the manner in which the requirements are set forth reflect the realities of the problems inherent in the design process combined with the problems and trade-offs that have to be made by the Program Manager? It is the responsibility of the Program Manager to maintain a balance between cost, schedule, and technical performance. We will next review these trade-offs of time, cost and performance factors and their impact on improving the "ilities".

PROGRAM TRADE-OFFS

The time parameter is one of the most critical factors affecting the endurance testing required to determine the durability characteristics of engine components. Endurance testing can not be initiated until the latter part of the development testing when the engine design has solidified to a major extent. Thus, if there are schedule slippages in the early stages of development without a commensurate extension of the development period or a shrinkage of the total development period the area that is most vulnerable to being reduced is that of endurance testing. An inadequate amount of endurance testing, regardless of the reason, will affect engine durability and, therefore, logistics costs in two ways. (3:38) First, the more endurance testing there is, the greater the number of failure modes that can be identified. Early identification of the greatest number of failure modes will permit incorporation of corrections into the engine design prior to or during the early stages of production thereby reducing the cost of modifications and early obsolesence of spare parts. Late identification of failure modes will increase logistic support costs for the same reasons. Secondly, the data generated during endurance testing is used to estimate the quantities of spare engines and spare parts that will be required to maintain the early operational fleet. These factors must be estimated as closely as possible to avoid the costs of overbuying and potential for an increased rate of obsolesence on the one hand and on the other, to avoid the costs that would be incurred by having to have the operational units stand down for a lack of spares.

To a certain extent, money can be used to offset deficits in time. Test hardware and the engine testing process are both relatively expensive commodities. However, if sufficient funds are available it is possible to obtain sufficient testing to offset any compression in time. Even if sufficient time is available, adequate funding of the test program is essential to reducing life cycle costs. If funds are limited neither the program manager nor the contractor can afford to risk test hardware any more than necessary to meet the minimum program requirements. Austere funding effectively precludes extensive and intensive endurance testing because of the potential risk to the hardware. The iterative process of engine design also makes it essential that adequate funding for testing be available. While creativity can not be purchased or scheduled an adequate test program will enhance creativity by enabling the test of new ideas which will generate new data which, in turn, may generate new ideas. It can be argued that the Program Manager of an austerely funded engine development program can not maintain program balance. The cost that should be incurred prior to MQT will be shifted to the post-MQT period with a resultant increase in logistics cost.

There are many performance factors associated with an engine. Three of the most important are the thrust-to-weight ratio, thrust and weight. The thrust-to-weight ratio has more of an impact on overall system performance than any other factor. However, when it becomes necessary to make trade-offs between performance and the "ilities" it is the components of this ratio, thrust and weight, that most adversely affect the "ilities". Thrust is a measure of the work being done by an engine. It can be increased by increasing temperatures, pressures, air flows or any combination thereof. An increase of any of these factors places additional stress on some engine parts. The additional stresses can, of course, be offset by making the affected parts stronger (i.e., heavier). However this would reduce the thrust-to-weight ratio and, in turn, overall system performance. Even if the thrust-to-weight ratio did not increase appreciably because of the increased weight, the additional weight would still not be permitted. System weight tends to increase by several pounds for every increase of a pound in engine weight.

This then is the dilemna of the engine program manager in the development phase to optimize engine performance on time and within cost he must maximize thrust and minimize weight through an iterative design process attempting to advance the state-of-the-art and maintain acceptable levels of safety, reliability, durability, and maintainability, etc. In the absence of any acceptable measurement yardstick, other than extensive testing which may be limited to time and/or dollars, the tendency to minimize the importance of the "ilities" is at least understandable.

PRODUCTION AND OPERATION PHASES

We will discuss the production and operational phases of an engine together as they frequently overlap. If the engine being developed is for an airframe being developed concurrently there is tremendous pressure to start delivery of production engines as soon as the MQT has been completed. In some instances, in fact, the contractor is given authority to release long lead parts to production prior to completion of MQT. Compounding the early release to production is the comparatively high rate of initial production. If the airframe uses a single engine, then the engines to be delivered are one for each airframe plus approximately an additional twenty-five percent for spares. If the airframe uses more than one engine the production rate increases accordingly. One of the problems with the high initial production rate is that, despite the severity of quality control procedures imposed, there are always problems in switching from basically a job-shop operation for the test engines to the production line for the operational engines.

The second, and most severe, problem is that the engine is not an mature product. In order to continue the maturation process the Air Force has developed the concept of the Component Improvement Program. The Army and the Navy conduct similar programs under the same or different names. During CIP there is an attempt to achieve two separate but complementary objectives. The first objective is identify the cause of, and develop a "fix" for, any flight revealed deficiency. These deficiencies can be either performance deficiencies or part failure. The second objective is to reduce cost and improve maintainability, reliability, and durability. Cost reduction effort generally follows two approaches: improve producibility and, select less expensive materials and/or designs.

There are two factors that, in the author's opinion, adversely affect the program managers ability to affect improvements to the "ilities" in the Component Improvement Program. The first factor is the lack of an adequate standard of measurement that can be used to determine what has been achieved to date. It is suggested that the factors used to establish achieved reliability and maintainability are too sensitive to subjective interpretation and not available on a timely enough basis to be used to reduce life cycle costs.

The second factor, depicted in figure three, is time. On the one hand, Component Improvement Programs are contracted for on an annual basis. However, it may take three or more years from the time an idea is generated, developed, reduced to test hardware, tested, incorporated in production engines, and used in an operational environment until sufficient data is available to determine the level of improvement obtained. Therefore, the worth of the contractors effort in any CIP increment can not be determined until two or more years after the end of the contract period. This situation makes it difficult for the engine program manager to motivate the contractor towards high achievement in the Component Improvement Program.

Despite the problems inherent in the engine acquisition process described in this section it is doubtful if substantial or basic changes to the process can be made. The Joint AMC/NMC/AFLC/AFSC Commander's

Panel on Aircraft Engine Acquisition concluded, in part, that "Although engine reliability/durability would be enhanced by longer development and increased development time (higher cost) than is now the practice, such an alternative does not necessarily provide the "best" program. It is not possible within real program constraints to achieve improved reliability/durability by making some drastic changes in the engine acquisition process."

If drastic changes to the process are not possible, what can be done to improve the process. In Section IV an approach for improvement will be offered for consideration.

SECTION IV

A SUGGESTED APPROACH

We have seen in the previous sections that there are many environmental factors affecting the engine development process that result in less than optimal attention being given to reliability and maintainability. We have also seen that designing for designing for engine reliability and maintainability would be extremely difficult even in the absence of these adverse environmental factors. It is the purpose of this section to provide, in conceptual form, an alternative procedure to those currently being used to obtain increased engine reliability and maintainability. It must be recognized that some improvement in reliability and maintainability could be obtained early in the production program if the development period was extended and the initial production rate was maintained at a very low level. However, the underlying assumption of the approach to be suggested is that neither the design process nor the engine acquisition process is susceptible to drastic change. Thus the approach being proposed acknowledges existing constraints and attempts to capitalize on the strengths of the existing process.

It is suggested that before we can satisfy the objective of improved reliability and maintainability, two elements must be present. First, an adequate standard of measurement and, secondly, an ability to motivate both Government and Contractor personnel towards improving these areas. To establish the adequacy of either element they must be evaluated against valid criteria. The author contends that the following criteria are sufficient for the purpose of evaluation.

For the standard of measurement:

1. The elements being measured must be easy to identify and measure.

2. The data gathering system must be simple and inexpensive to operate.

3. Neither the standard nor the method of measurement should be subject to misinterpretation or distortion.

4. The standard should be measurable and provide information on a timely basis.

For the motivational factor:

1. It should attract the attention of both the contractor and government program manager.

2. It should not penalize the contractor or the Government for factors outside of their control.

3. It should provide rewards for outstanding performance.

The Standard of Measure

It is suggested that both a unit of measure and a standard of measure that satisfies the above criteria can be established on the basis of the following ratio:

$$\frac{\text{actual number of maintenance actions per time period}}{\text{actual number of engine run hours per time period}}$$

The "actual number of maintenance actions per time period" would be defined as the total number of scheduled and unscheduled maintenance actions, exclusive of the two categories defined below, initiated during any given time period. The two categories of maintenance actions that should not be included are those maintenance actions necessitated by flying object damage (FOD) and those maintenance actions not required by reason of an engine problem (i.e., the transfer of an engine from one airframe to another because of a problem in the first airframe). The "actual number of engine run hours per time period" is self explanatory. Both items of data are measured and accumulated by existing Air Force data systems.

In order to use this ratio as a standard for comparison the "actual number of maintenance actions" must be converted to "equivalent maintenance actions" which would be developed in the following manner: First, from the technical manuals determine or estimate the number of scheduled maintenance actions required at each level. Then, determine the average number of hours required per maintenance action per level and develop an equivalent number of scheduled maintenance actions per engine run hour (any standard number of hours can be used as a base). The average time per action could be established through standard industrial engineering techniques. As an example, suppose it was determined that for every 1000 engine run hours the number of scheduled maintenance actions were five at base level, averaging one hour each, two at intermediate level, averaging five hours each, and one at depot using 20 hours. The number of equivalent scheduled maintenance actions per thousand engine run hours would be

$\frac{(5 \times 1) + (2 \times 5) + (1 \times 20)}{1000}$ or 35 equivalent scheduled maintenance actions per thousand engine run hours. The number of expected unscheduled equivalent maintenance actions would be developed in the same manner except that the expected number of unscheduled maintenance actions would have to be established through estimation techniques or, if we are to use the ratio as a means of contractor performance, through negotiation with the contractor. The sum of the scheduled and unscheduled equivalent maintenance actions per 1000 engine run hours could then be used as a standard which can be used for comparison against actual performance.

There are five primary reasons why equivalent maintenance actions is used in lieu of actual maintenance man hours. First, for easy identification and measurement. It is much easier to count the number of maintenance actions by maintenance level for any period of time than it is to count manhours. Secondly, once the number of maintenance actions by level were accumulated, the number of equivalent maintenance actions can readily be determined by multiplying the number of actions by the respective standard average number of hours, Thus, the data system should be easy and inexpensive to operate. Thirdly, if actual manhours are used there can be a problem of proper allocation of manhours in a multi-engine maintenance shop, which could result in misinterpretation or distortion of the data. Fourthly, reports can be submitted on a much more timely basis under this procedure than if we used man hours. Finally, and perhaps most importantly, if we are to use the standard as a contract management tool it must be free of variances caused by differences in the expertise and skill levels between maintenance shops that would be reflected in actual man hour counts.

It is envisioned that this standard of measure would be used in the following manner. The development contract would establish goals in terms of equivalent maintenance actions per thousand engine run hours to be achieved by each production lot of engines. The contract would establish a band of acceptability for each goal and clearly state that all maintenance actions under all circumstances except those identified above, would be used to determine whether or not the goals had been achieved. The goals, to be effective, would have to be established objectively and at the same time provide a difficult but not impossible challenge for the contractor. The rationale for the band of acceptability surrounding each goal is to make allowances for the variances in the number of maintenance actions that are caused by different mission profiles (i.e., a training squadron as opposed to an operational squadron). During flight test the contractor could gain sufficient data for him to determine what improvements are needed to achieve the established goals. This data would continue to be generated by Air Force units and provided to the contractor to be used in developing more improvements in the Component Improvement Program. At the end of one year after the delivery of the last engine in each lot the data generated for that lot would be evaluated to determine how well the contractor had performed in relationship to the established goal.

The above standard of measurement appears to satisfy the criteria for an adequate standard of measurement. Further, it would seem logical that as we decrease the ratio of equivalent maintenance actions per 1000 engine flight hours our reliability and maintainability will increase. The next question to be answered is how do we motivate both government and contractor personnel to achieve these goals.

THE MOTIVATIONAL FACTOR

Of the motivational tools available, the author has concluded that the most viable tool is one that is based on financial incentive and constraints associated with a particular engine model. This conclusion was reached partially on the basis that once an engine manufacturer has initiated production he is in a sole source position for future requirements for that engine. Assuming that the achieved level of reliability is marginally acceptable and therefore would not adversely affect future sales any increase in the achieved level would only result in a decrease in his sale of spare parts. The other factor that contributed to reaching the stated conclusion is that the alternative motivational factor available, the prestige and enhanced reputation that may be obtained from reaching a high level of reliability does not seem to have been a sufficient motivator in the past. There are, possibly, two reasons for this. First, attaining a high level of reliability on one engine does not necessarily mean that the same level can be achieved on another engine. Secondly, it is suggested that a high achievement level has not resulted in a high prestige factor but, rather, merely in the reduction in the number of customer complaints.

One of the difficulties encountered in attempting to establish a motivational factor based on financial incentives and constraints is determining where, during the development and production period, the incentive should be applied. As noted in Sections II and III, it may take as long as two, three or more years before an idea can be incorporated in production engines and sufficient data becomes available to enable an evaluation of the results of this change. Although this situation seems to imply that the incentives should be applied to the production engines, it must be recognized that the actual development efforts were accomplished under a different contract or contract line item.

It is suggested that in order to resolve this dilemna it is necessary to ignore the contractual time limitations and view each contractual relationship as elements of a total program rather than as entities in themselves. Once we take this broader view we can then establish constraints to the development process and apply the incentives to the demonstrated achievements of the production engines.

In the discussion of the standard of measure it was suggested that the standard of measure could be used to establish goals for each production lot. Let us assume that the following goals in terms of the proposed standard of measure have been established for several production lots:

	LOT I	LOT II	LOT III	LOT IV
Maximum Acceptable	150/1000*	120/1000	100/1000	90/1000
Reward Goal	75/1000 *	60/1000	58/1000	55/1000

*equivalent engine maintenance actions/1000 engine run hours.

It is suggested that positive and negative incentives can be contractually established for each goal through the use of a modified award fee concept.

An award fee is normally used to reward contractors for outstanding performance on an existing cost-plus contract in areas that can't be measured precisely, such as management. The modifications that are necessary are first, the award fee would have to be placed against a tangible factor; the achievement of the reward goal. Second, the award fee would have to be established for both a positive and negative amount; a reduction of a stated amount of profit for exceeding the maximum acceptable level and a bonus for achieving a level less than the reward goal. Third, the award fee would be associated with the production contract element with the fee being payable after one years experience with the engines from that production lot and prior to final settlement of cost and profit for that lot. These modifications are, of course, necessitated by the time it takes to get valid operational data which has been previously discussed.

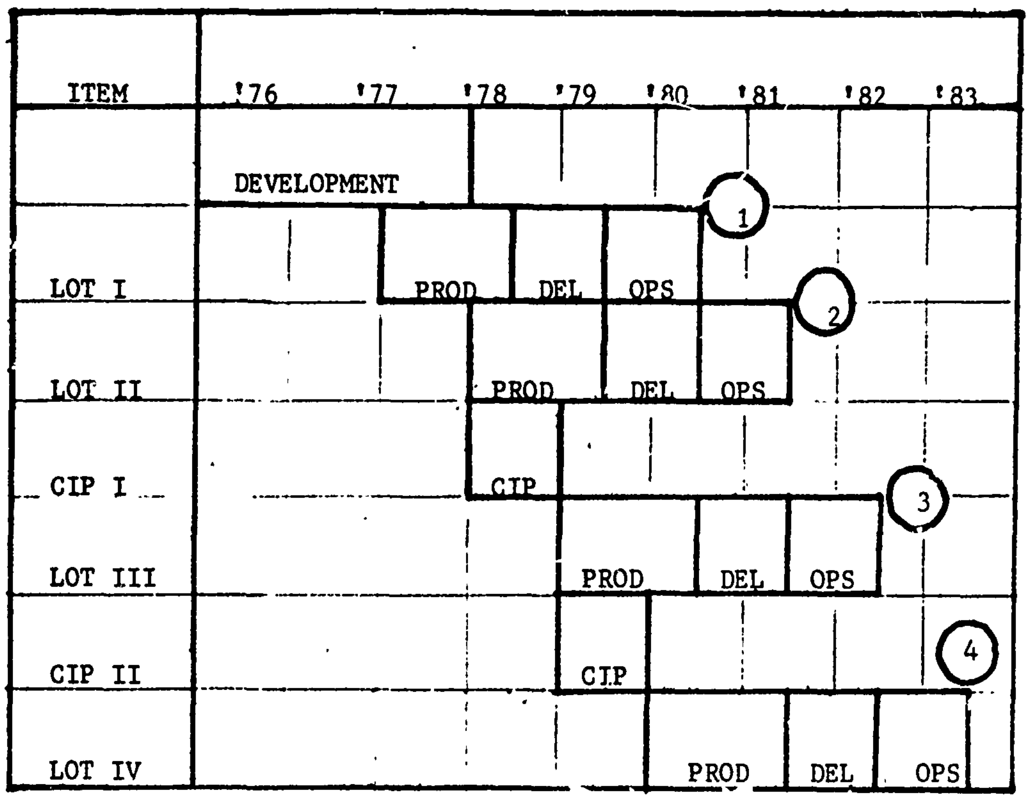
In order to obtain the contractor's acceptance of a negative award fee certain constraints would have to be placed on the development elements of the contract. These constraints are necessitated by the fact that the contractor has no control over the amount of funding that will be made available nor any guarantee that the Government will agree to proposed engineering changes. The first constraint would center on the amount of funds that would be available in each of the development increments to support reliability and maintainability effort. It is visualized that the development contract would establish a level of funding, within the estimated cost, necessary to support achieving a level below the maximum acceptable established for the first two production lots. In the event of a contract change that affected this funding level, one of the trade-offs that could be negotiated would be a relaxation in the maximum acceptable level. The first CIP increment would have a similar level of funding but it would be related to the goals established for the third production lot. Each successive CIP increment would be treated in a similar manner. The argument will be made that the first time a contract change is contemplated the contractor will seek a relaxation in the maximum acceptable boundary. In all probability that will be what happens. However, if the issue is brought up during negotiation, it can be dealt with on an objective basis by both the Government and the contractor. If the issue is not raised, then the maximum acceptable boundary will remain in effect. Most importantly, however, it will cause both the contractor and the Government to consider the impact of any change on reliability and maintainability.

The second constraint centers on engineering changes and the Governments ability to pay for them. Again it will be argued that the contractor will demand relaxation of the maximum acceptable boundary in the event of Government disapproval of an engineering change. If this is the case then the above discussion of the funding level is equally applicable.

It appears that this approach satisfies the criteria set forth above. It will retain the attention of both the Government and the contractor. Neither party will be penalized for factors outside their control. Finally, rewards are available for outstanding performance. A graphic portrayal of this concept is indicated in figure 3.

FIGURE 3

ENGINE MAINTENANCE ACTION MEASUREMENT POINTS



1 Achievement resulting from development measured.

2 Achievement resulting from development measured.

3 Achievement resulting from CIP I measured.

4 Achievement resulting from CIP II measured.

In summary, an alternative management procedure for obtaining improved reliability and maintainability has been offered in this section. It is believed that once the necessary standards were established it could be implemented with some degree of success in every active engine program.

SECTION V

SUMMARY AND CONCLUSION

The process of developing, producing, and deploying an engine is, at best, a lengthy, difficult and complex process. The overview of an engine life cycle and the costs associated with each phase led, in Section II to an examination of some cost models that indicated that life cycle costs could be reduced through a relatively modest investment in reliability during the pre-MQT development period.

The reasons for not fully exploiting this potential were examined in Section III. It was found that, in comparison to an electronic reliability engineer, the engine reliability engineer is faced with many difficult problems. The "build it, break it, rebuild it" engine design process contains inherent problems, with respect to reliability and maintainability, unless there were sufficient money and time available to conduct a desirable amount of testing. An examination of the pressures and trade-offs faced by the program manager led to the conclusion that during the pre-MQT development period the predominant area of concentration was focused on obtaining maximum performance in the engine. A collateral finding was that it was difficult to determine the level of reliability and maintainability being achieved at any point in time. These factors result in minimal attention being paid to the areas of reliability and maintainability during the pre-MQT development period.

The purpose of this paper was to offer an approach that could be used to obtain increased reliability and maintainability during the engine acquisition cycle. This purpose was achieved in Section IV. It was not intended to suggest that the proposed approach would be a panacea for all the problems in the engine design process. Further, it is expected that there will be many challenges to the validity of the concept proposed. Some of these challenges may have merit and it may be necessary to refine the suggested approach to some degree. However, it is believed that the approach suggested provides the program manager with a tool to manage reliability and maintainability improvements than is now available.

In conclusion, the engine acquisition process is beset by many problems that tend to deemphasize reliability and maintainability. The approach suggested herein should provide the engine program manager a tool that will enable him to place in their proper place the appropriate degree of emphasis on reliability and maintainability and achieve maximum reductions in life cycle cost.

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